TPF-5(179) QPR #06

Evaluation of Test Methods for Permeability (Transport) and Development of Performance Guidelines for Durability

Quarterly Progress Report

To the

Pooled-Fund Research Program

(The participating states are: FHWA, Indiana, Michigan, Minnesota, Illinois, Kansas, Montana, Pennsylvania, Iowa, New York, and Colorado)

For the Period of

October 1st, 2009
to
December 31st, 2009

Limited Use Document

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Prepared by Indiana Department of Transportation, Purdue University, and the National Ready Mixed Concrete Association

Figure 1: Overall Project Schedule

		Project Months																								Estimated
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Completed
Phase I:	**Literature Review of Concrete Permeability (Transport) Test Procedures and Models that Link Tests with Performance**																									
	Task 1: Literature Review	15	30	45	75	80	90	90	90	90	90	90	90	90	90	90	90	95	95							95
	Task 2: Prepare a Description of Each Procedure		5	15	25	30	90	90	90	90	90	90	90	90	90	90	90	95	95							95
	Task 3: Develop a Summary Document					10	30	50	70	90	90	90	90	90	90	90	90	95	95							95
Phase II:	**Evaluate of Promising Concrete Permeability (Transport) Tests and Recommend Procedures For Further Use**																									
	Task 1: Prepare Reference Concretes	15	25	40	60	60	80	80	80	80	80	80	80	80	80	80	80	80	80							80
	Task 2: Describe Constituent Materials			10	20	40	40	80	80	80	80	80	80	80	80	80	80	80	80							80
	Task 3: Develop Reference Material			15	15	20	40	40	40	50	50	50	60	60	65	80	80	80	80							80
	Task 4: Perform Tests					20		10	20	30	40	40	50	50	60	80	80	80	80							80
	Task 5: Evaluate Testing Procedures					20						20	25	30	35	35	35	35	35							35
	Task 6: Recommedations to Existing Procedures													10	10											10
Phase III:	**Develop New or Improve Existing Permeability (Transport) Testing Procedures. Develop Protocols to Use these Tests, Evaluate the Precision and Bias of Tests**																									
	Task 1: Develop Modified Tests					10							10	10	10	25	25	25	25							25
	Task 2: Evaluate Modified Tests															10	10	10	10							10
	Task 3: Develop a Report of Modified Tests															10	10	10	10	■	■	■				10
	Task 4: Develop New Testing Procedures														■	■	■	■	■	■	■	■	■	■	■	~
	Task 5: Perform New Testing Procedures																10	10	10						■	10
	Task 6: Evaluate New Testing Procedures																									~
	Task 7: Develop a Summary Document with Recommendations																									~
Phase IV:	**Correlate Permeability (Transport) Tests with Laboratory Tests that Evaluate Durability**																									
	Task 1: Prepare Specimens	5	15	25	45	65	65	70	75	80	85	90	90	90	90	90	90	90	90							90
	Task 2: Condition Specimens			10	25	30	30	35	40	45	50	50	55	60	65	65	65	65	65							65
	Task 3: Expose Specimens													60	10	10	10	10	10							10
	Task 4: Evaluate Specimens													60												60
	Task 5; Perform ASTM Tests								20	20	20	40	50	50	55	55	55	55	55							55
	Task 5: Evaluate Field Structures																									~
	Task 6: Develop Recommendations																									~
	Task 7: Develop a Summary Document																									~
Phase V:	**Develop Performance Criteria Guidelines that Link Permeability (Transport) Tests with Exposure Conditions and Anticipated Performance**																									
	Task 1: Prepare Draft of Criteria																									~
	Task 2: Address SAC Comments																									~
	Task 3: Prepare Revised Draft of Criteria																									~
Phase VI:	**Preparation of Techonology Transfer and Educational Materials**																									
	Task 1: Prepare Materials																									~
Deliverables								1																		~
Study Advisory Committee Meetings							1		■																	~

Continued

		Project Months																								Estimated
		25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	Completed
Phase III:	**Develop New or Improve Existing Permeability (Transport) Testing Procedures. Develop Protocols to Use these Tests, Evaluate the Precision and Bias of Tests**																									
	Task 1: Develop Modified Tests																									~
	Task 2: Evaluate Modified Tests																									~
	Task 3: Develop a Report of Modified Tests																									~
	Task 4: Develop New Testing Procedures	■																								~
	Task 5: Perform New Testing Procedures	■	■	■	■	■	■																			~
	Task 6: Evaluate New Testing Procedures						■	■	■																	~
	Task 7: Develop a Summary Document with Recommendations								■	■	■															~
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	Task 3: Expose Specimens																									~
	Task 4: Evaluate Specimens			■			■	■	■	■	■	■	■													~
	Task 5; Perform ASTM Tests	■	■	■	■	■	■	■	■	■																~
	Task 5: Evaluate Field Structures								■	■	■	■	■													~
	Task 6: Develop Recommendations												■	■	■											~
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Phase VI:	**Preparation of Techonology Transfer and Educational Materials**																									
	Task 1: Prepare Materials																					■	■	■		~
Deliverables											2						3				4			5		~
Study Advisory Committee Meetings												■													■	~

1 - Phase I draft report
2 - Phase III draft report
3 - Phase IV draft report
4 - Phase V draft report
5 - Phase VI draft report

Figure 2: Estimated Project Expenses

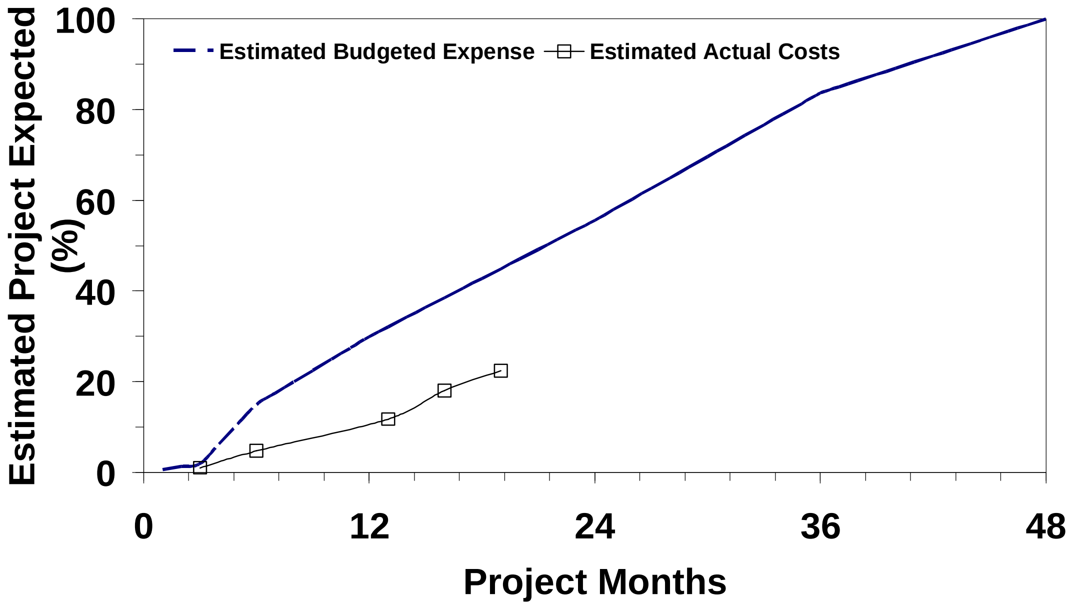


Figure 3: Project Budget and Expenses

Category	Detailed Description	Budgeted Cost	Billed Expense Through 12/30/09
Personnel			
	INDOT Staff (Tommy Nantung*)	~	~
	Purdue Faculty (Jason Weiss and Jan Olek)	$ 121,230	
	Post-Doctoral Research Assistant/Visiting Faculty	$ 168,240	
	Graduate Students	$ 177,848	
	Undergraduate Students	$ 8,679	
	Laboratory Technician	$ 29,343	
Laboratory Expenses			
	Scientific Equipment	$ 62,000	
	Laboratory Supplies/Expendables	$ 13,000	
Travel			$ 126,123
	Domestic Travel	$ 8,400	
Office Expenses			
	Communications	$ 3,000	
	Supplies and Expenses	$ 4,760	
	Printing and Duplication	$ 6,500	
Study Advisory Expenses			
	Participant Travel to SAC	$ 54,000	
	Meeting Expenses	$ 6,000	
Subcontracts			
	NRMCA Consultants	$ 220,000	$ 71,790
Total			
		$ 883,000	$ 197,913

1.0 Summary of Progress

This report provides an update from the sixth quarter of the project. It covers the three month period ending December 31st 2009.

During the reporting period work was performed primarily on Phases I and II. Additional work was preformed on Phases III and Phase IV.

1.1 Phase I – Literature Review

The research on Phase I is focused on performing an extensive review of literature pertaining to the measurement of permeability (transport) in concrete. To date the research has focused on collecting a complete listing of papers and test methods currently in existence nationally and internationally for determining permeability. The post-doc working on this project, Amir Pourasee, is completing this project as this is the main focus of his current work. To manage the data obtained from this literature review the research team is developing a summary of each existing permeability (or transport) test that includes:

- a description of the scientific principle behind a particular test,
- the application of the test,
- the size and conditioning of the specimens used in the test,
- the testing procedure,
- the methods used to evaluate the test,
- the advantages and disadvantages of a particular test,
- the length of time that a test takes to perform,
- the commercial availability of the test procedure/equipment, and
- an approximate cost and availability of the testing equipment.

The test methods will then be separated according to like scientific principles of operation and the most promising methods will be recommended for further study in phase II.

This data is being gathered from a conventional literature review that will make use of indexes such as the web of science, TRIS, COMPENDEX, NTIS, SHRP concrete and structures program, PCI, ACI, and AASHTO. In addition, surveys are being developed to be distributed to each state or agency to determine which permeability (transport) test procedures they are currently using. Additional surveys will be sent to International countries and test equipment manufactures

At the completion of Phase I, a report will be prepared that provides a review of the literature on permeability (transport) test methods. This will include the summaries as well as a thorough comparison of the methods and recommendations for Phase II.

1.2 Phase II – Evaluate Promising Concrete Permeability (Transport) Tests

The research on Phase II is focused on evaluating several reference concrete mixtures. To fully evaluate the most promising tests, specimen curing, specimen conditioning (duration and relative humidity), sample size, air content, specimen maturity, and variations in mixture proportions that may be anticipated during construction will also be evaluated. This will enable the most promising test methods to be assessed and will indicate the resolution, repeatability, and robustness of these test procedures. Aspects associated with determining the influence of curing procedures, conditioning and curing duration will also be evaluated.

Purdue has assembled materials and prepared samples for conditioning so that the samples can be adequately conditioned. A series of samples have been prepared and are currently conditioning. This includes several of the reference water to cement ratio mixtures. In addition samples have been collected from the field. Testing has begun however additional test methods are still being identified and some samples are still being conditioned. Specific focus has been placed on electrical resistance methods and sorption measures to provide good baseline measurements.

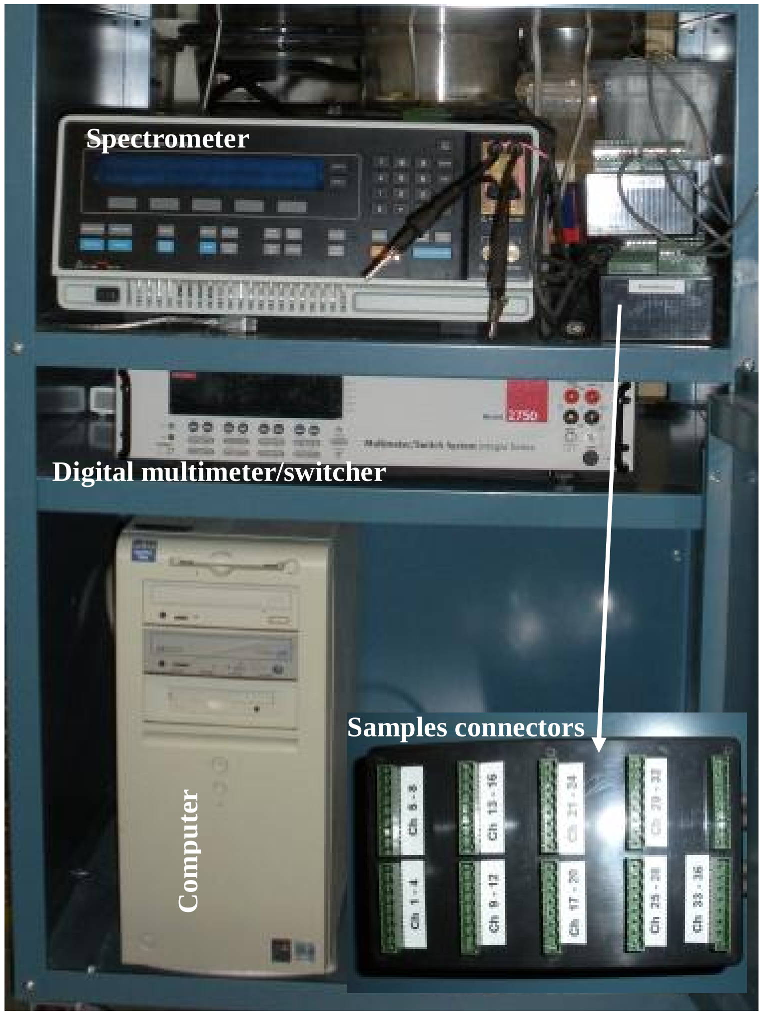
In addition, the research team has placed several samples at in the field at the INDOT test site to evaluate the internal humidity that can be expected in Indiana given five exposures. The exposures will include a 50% environment (indoors), a submerged sample, a vertical surface, a horizontal surface on a drainable base and a horizontal surface on a non drainable base. The team used a series of deployable sensors and have developed an approach whereby this can be done in other locations.

Since electrical impedance measurement techniques are being increasingly used to measure material property development and permeability of concrete and other cement based materials; an automated electrical measurement system (AEMS) for measuring the properties of cementitious materials has been developed and used is this projects. Figure 4 shows a view of the designed system. A copy of the published paper based on the AEMS is attached to the report.

Cylinders have been prepared with different w/c and their electrical impedance has been continuality monitored. The impedance of the materials will be related to the permeability of the materials. In addition to the electrical impedance measurements on the mortart and concrete, pore solution has been expressed from these materials for use in interpreting the results.

The research team also visited European laboratories during the fifth quarter (during a separately funded source) and performed a review of techniques that have been used there. Based on this review two test methods are currently being developed which will include a method based on the South African oxygen permeability test and a test based on a test that is utilized by the Swiss. In addition, the Swiss have agreed to assist in using several European tests that they have at EMPA. The South African oxygen permeability test equipment has been commissioned and was received in early January. Specimens are being prepared and testing developments are underway.

Figure 4: A view of the new designed system (AEMS) to assess electrical properties in concrete



The South African test method sets out the procedure for determining the oxygen permeability index. Specimen age may have a significant effect on the test results, depending on the type of concrete and the curing procedure. The oven drying procedure has been selected to result in the minimum degree of micro-structural alteration of the concrete specimens, while still giving minimal uniform moisture content. In addition other conditioning methods will be analyzed. The test specimens considered in this method statement are circular discs prepared by coring and cutting concrete cubes in the laboratory, or by taking cores from concrete elements on site. Each test specimen shall consist of a 70 ± 2 mm diameter, 30 ± 2 mm thick concrete disc.

X-ray attenuation radiography is also being used to study the water permeability and fluid ingress in cementitious materials. X-ray attenuation measurements are based on the concept that as x-rays pass through a material, some of the x-ray's intensity is attenuated by the material while a portion of x-rays passes through the material and is captured using an x-ray camera. The radiation that is attenuated is related to the density of the concrete. This can be used to measure the cracks in concrete since as solution fills the crack and begins to penetrate the pores in the concrete, the concrete becomes more dense.

Some of the results of using this system is prepared for publication and a draft of the paper is attached to his report. In addition, moisture ingress in sound samples has been studied and the results were published which are also attached to this report.

The NRMCA Research Laboratory (NRMCA-RL) is currently conducting several tests including

Rapid Index tests in Concrete

- Rapid Chloride Permeability test (ASTM C1202/AASHTO T277)
- 5 minute Conductivity test
- Rapid Migration Test (AASHTO TP 64)
- Sorptivity Test (ASTM C1585)
- Absorption Test (Modification of BS122 being drafted in ASTM subcommittee C09.66)

All the rapid index tests use a 4" diameter by 2" thick specimen that has been cut from the top of a 4x8 concrete cylinder.

Slower Performance Tests in Concrete

- Chloride Diffusion (ASTM C1556)
- Freeze Thaw (ASTM C666)

The Rapid Index Tests are evaluated to see if they correlate with the slower performance tests. The rapid index tests and criteria that correlate well with the performance tests can be used in performance specifications. More discussions on the mixture proportions evaluated, tests conducted, curing conditions and preliminary results available thus far are provided.

The 5 minute Conductivity (ASTM Draft) test is similar to the Rapid Chloride Permeability test (ASTM C1202) except that it uses a 0.3N sodium hydroxide solution on both sides of the cell and the test is run only for 5 minutes after which the current reading (I) is noted while applying a constant voltage of 60V. Conductivity is calculated as, □ $(S\text{-}m^{-1}) = l/RA$, where R=concrete resistance (R-Ω) calculated from Ohm's Law as R= V/I, A=specimen cross-sectional area, *l* = specimen length.

After the moist curing period the absorption test (ASTM Draft) involves oven drying at 50°C for 72±2h followed by cooling for 24±0.5h in a dry airtight vessel. Then, the specimen is immersed in the water for 30±0.5 min and immediately the mass is determined for calculation. Absorption is calculated as a percent increase in mass.

2.0 Proposed Activities for the Next Period

The research team had a SAC meeting during Quarter 3. It is anticipate that the next QPR will be held during the spring of 2010.

2.1 Phase I - Literature Review

The research team is completing the literature review and providing a draft to the stakeholders for review and discussion. This is near completion and is being completed by Amir Pourasee who is a post-doctoral associate that has been added to this project. This is the main task that he is currently working on so that this can be brought to completion.

2.2 Phase I - Survey of Permeability Test Methods

A survey of permeability test methods was prepared and sent to DOT, material suppliers and testing labs that evaluates the current state of the practice as it relates to permeability (transport tests). The survey outlined the most common tests used in the US. Data from the survey has been used in guiding the research program. Amir Pourasee is currently completing this phase of the research. Purdue ended up performing this task.

2.3 Phase II - Sample Preparation and Conditioning

Work will continue to prepare the reference concrete for Phase II and IV. The constituent materials will be fully characterized and the samples will be conditioned using both accelerated and natural curing conditions. Javier Castro, a graduate assistant and Phil Kompare a graduate assistant are currently working on this research.

The renovation of the new laboratory was completed at the end of October and a new conditioning room is now available. In addition the laboratory is ready to begin to make samples for use in Phase IV. Pending final validation of the relative humidity and temperature control a large number of samples can be exposed to conditioning at that time. The electrical impedance of the concrete materials is been measured continuously and results will be reported at the next progress meeting

The Swiss gas permeability device has been designed and ordered. The Swiss have also offered to test a small number of samples in a variety of equipment to provide additional data for comparison. It is currently anticipated that the equipment will be in place for testing at the end of the next quarter. The research team has samples conditioning so the research can start as soon as the devices being ready.

Samples with different w/c of 0.3, 0.42, and 0.5) have been prepared according to ASTM G109, as shown in Figure 5.

Figure 5: Samples Prepared According to ASTM G109

These samples are exposed to 3% sodium chloride solution. Potential difference between top and bottom rebars is monitored, using a new designed automated system every hour. In addition, the potential will be controlled manual to check the accuracy of the new system. The potential difference between top and bottom rebars indicates the macro-cell corrosion of the top rebar. The micro-cell corrosion of the top rebar will also be measured every month by using different electrochemical techniques such as Linear Polarization Resistance (LPR), Electrochemical Impedance Spectroscopy (EIS) and Cyclic polarization. The corrosion products will be determined using electrochemical techniques such as cyclic voltametry.

The outcome of this research will be used to evaluate the permeability of concrete made with different mixture proportions.

2.4 Phase IV NRMCA

It is understood that concrete can fail due to chloride induced corrosion, sulfate attack, freeze thaw attack and ASR. In this phase rapid index test criteria suitable for specifications will be developed that correlate well with slower performance tests for concrete exposed to chlorides, sulfates, and freeze thaw.

Chloride Ingress - Test Methods, Curing Conditions and Test Ages

Chloride ingress can occur from deicing salts applied in bridge decks in Northern regions as well as concrete exposed to marine conditions. It is well known that when the chloride concentration at the steel rebar exceeds the chloride threshold corrosion can initiate. The chloride diffusion test (ASTM C1556) is understood to be a good performance test. However, that is a very slow test and applicable only for sophisticated laboratories. So rapid index tests were evaluated as follows:

Mixture Proportions and Variables

w/cm	PC	15%FA	30%FA	25%SL	50%SL	7%SF	40%SL+5%SF
0.29	Yes - l						
0.34							Yes - n
0.39	Yes - m	Yes - l	Yes - vl	Yes - l	Yes - vl	Yes - vl	
0.49	Yes - h	Yes - m		Yes - m			
0.62			Yes - h		Yes - h		

where

H – High chloride permeability (>5 x 10^{-12} m^2/s) – 3 mixtures
M – moderate chloride permeability (3 to 5 x 10^{-12} m^2/s) – 3 mixtures
L – low chloride permeability (2 to 3 x 10^{-12} m^2/s) – 3 mixtures
VL – very low chloride permeability (0.7 to 2 x 10^{-12} m^2/s) – 3 mixtures
N – negligible chloride permeability (<0.7 x 10^{-12} m^2/s) – 1 mixture

The above mixtures were selected keeping the following in mind:

1. Cover a predicted (based on Life 365 computer program) 2 year chloride diffusion coefficient range that is broad – 6.8x10^{-12} to 0.62x10^{-12} m^2/s
2. To be able to use rapid index test criteria to eliminate mixtures with high diffusion coefficients (>5 x 10^{-12} m^2/s)
3. To be able to use rapid index test criteria to choose mixtures with desired classification as indicated above
4. Look at common SCMs like fly ash, slag, silica fume to see if correlation between the rapid index tests criteria and diffusion coefficients are independent of SCM types and dosages
5. w/cm, SCM dosages must cover the ranges normally used in HPC
6. Also some mixtures that would yield high chloride diffusion coefficients (containing high w/cm, high pozzolan) should be made and the rapid index tests should yield high values so that such mixtures will not be selected. Also some mixtures that would yield low chloride diffusion coefficients (containing low w/cm, low or no pozzolan or conductive aggregates) should be made and the rapid index tests should yield low values so that such mixtures will be selected.

Mixture Prepared and Tested Thus Far

All the 13 concrete mixtures have now been cast in 2 phases. Phase I looked at 6 mixtures and the test results are provided in Table 1 where as Phase II looked at 7 mixtures and the test results are provided in Table 2. The common elements of the two phases are:

Crushed coarse aggregate (1.0 in. nominal maximum size) ASTM C33 No. 57, natural sand FM=2.88
Adjusted water reducer or high range water reducer (if any) for desired slump = 5 to 7 in.
Non air entrained concrete mixtures – even though most of these mixtures in practice will contain air our aim here is to determine the validity of the rapid index tests and criteria in classifying mixtures based on their chloride diffusion coefficients. This validation will also hold for air entrained concrete mixtures. Also the use of air entrainment will make the comparisons between mixtures more challenging

Planned Test Methods, Curing Conditions and Test Ages

Normal Curing – Standard moist room curing starts immediately after making the specimens
Accelerated Curing – 7 days of normal curing followed by 21 days of curing in 100F water

For all mixtures measure the following:
Slump, temperature, air content, density, Strength (28 days), Shrinkage (7 days moist curing followed by 90 days of air drying). Shrinkage test is for reference and may be discontinued for future mixtures.

The following durability tests will be conducted for all the mixtures

Durability Tests

- **Rapid Chloride Permeability test – RCPT (ASTM C1202)**

i) 28 day accelerated
ii) 56 day normal curing
iii) 26 week (182 d) normal curing
iv) 78 week (546 d) normal curing

- **5 minute Conductivity Test (ASTM C1202 based)**

i) 28 day accelerated
ii) 56 day normal curing
iii) 26 week (182 d) normal curing
iv) 78 week (546 d) normal curing

- **Rapid Migration Test - RMT (AASHTO TP 64)**

i) 28 day accelerated
ii) 56 day normal curing
iii) 26 week (182 d) normal curing
iv) 78 week (546 d) normal curing

- **Chloride Diffusion Test (ASTM C1556)**

i) 56d (8 week) normal curing + 126d (18 week) in solution till 26 weeks. For Phase II this condition was replaced by 56d (8 week) normal curing + cyclic exposure (75 week using 3d in solution/4d at 73F-50%rh cycle) in solution - 2
ii) 56 d (8 week) normal curing + 490d (70 week) in solution till 78 weeks. For Phase II this condition was replaced by 6months normal curing + 12 months in solution - 1
iii) 56d (8 week) normal curing + cyclic exposure (18 week using 4d in solution/3d at 100F-20%rh cycle) in solution till 26 weeks. For Phase II the cyclic exposure was 21 weeks using 3d in solution/4d at 73F-50%rh.
iv) 56d (8 week) normal curing + 35d (5 week) in solution till 13 weeks
v) 26 weeks normal cure +35 days in solution

- **Sorptivity Test (ASTM C1585)**

i) 28 day accelerated + 18 d specimen conditioning (C1585)
ii) 56 day normal curing + 18 d specimen conditioning (C1585)
iii) 26 week (182 d) normal curing + 18 d specimen conditioning (C1585)

- **Absorption test BS 1881:122** – use latest ASTM draft at 50C

i) 10 day normal curing + 3 d in oven
ii) 28 day accelerated + 3 d in oven
iii) 26 week (182 d) normal curing + 3 d in oven
For Phase II only the 56 day normal curing condition was tested.

Rapid index tests need to correlate with chloride penetration levels for two real life situations:

a. when the structures are in a complete or near complete saturation state such as in a submerged marine exposure or possibly bridge decks in high humidity regions where chloride ingress is primarily diffusion controlled. The ASTM C1556 would be the correct comparison test here and the aim would be to observe which of the rapid index tests correlates well with diffusion coefficient (at oldest age).
b. when the structures are not completely saturated such as bridge decks in low humidity regions where the chloride ingress could be due to sorption and diffusion. ASTM C1556 conducted in a wet/dry scenario would be the correct comparison test here and the aim would be to observe which of the rapid index tests correlates well with the ingress coefficient (at oldest age).

Table 1. Yield Adjusted Mixture Proportions and Test Results – Chloride Phase I

Calculated Batch Quantities						
	0.49Ctrl	**0.49SL25**	**0.39SL50**	**0.49FA15**	**0.39FA30**	**0.34SL40SF5**
Type I/II cement, lb/yd^3	554	416	306	472	431	382
Slag, lb/yd^3		139	306			277
Fly ash, lb/yd^3				83	185	
Silica Fume, lb/yd^3						35
SCM, %	0	25	50	15	30	45
Coarse Agg. (No.57), lb/yd^3	2075	2074	2070	2081	2081	2086
Fine Aggregate, lb/yd^3	1303	1293	1314	1273	1267	1264
Mixing Water, lb/yd^3	272	272	239	273	240	236
w/cm	0.49	0.49	0.39	0.49	0.39	0.34

ASTM C494 Type A, oz/cwt	4.0	4.0	4.0	4.0	4.0	4.0
ASTM C494 Type F, oz/cwt	2.5	2.9	4.3	2.4	5.0	7.8
Fresh Concrete Properties						
ASTM C143, Slump, in.	7 1/2	4 1/2	8	7	6 3/4	9
ASTM C231, Air, %	1.4	1.7	1.3	1.5	1.6	1
ASTM C138, Density, lb/ft^3	156.5	156.1	157.7	155.7	156.5	159.3
ASTM C1064, Temperature, °F	76	76	75	76	75	75
Hardened Concrete Properties						
ASTM C39, Compressive Strength, psi						
28 days	6,830	7,550	10,520	6,640	7,970	12,440
Draft ASTM Standard, Water Absorption Test at 105 °C, %						
10d normal cure	2.89	2.24	1.69	3.25	2.33	1.43
28d accelerated cure	2.52	1.77	1.34	2.44	1.63	1.26
196d normal cure	2.30	1.80	1.29	2.29	1.44	1.49
ASTM C1202, Rapid Chloride Permeability, Coulombs						
28d accelerated cure	4657	1992	561	2414	723	166
56d normal cure	4674	1912	581	3013	1417	270
196d normal cure	3356	1581	496	1551	340	147
Draft ASTM Standard, 5 minute Conductivity, Sm^{-1}						
28d accelerated cure	0.019	0.009	0.003	0.009	0.003	0.001
56 normal cure	0.015	0.007	0.003	0.013	0.006	0.001
196d normal cure	0.010	0.005	0.002	0.006	0.002	0.001
AASHTO TP64, Rate of Penetration (RMT), mm/(V-hr)						
28d accelerated cure	0.065	0.030	0.004	0.046	0.015	0.003
56d normal cure	0.044	0.025	0.006	0.043	0.024	0.002
196d normal cure	0.047	0.016	0.006	0.025	0.006	0.002
ASTM C157, Length Change (Drying Shrinkage), %						
28 days[+]	0.035	0.039	0.031	0.029	0.028	0.028
56 days[+]	0.046	0.048	0.037	0.039	0.036	0.032
90 days[+]	0.055	0.054	0.044	0.048	0.043	0.039
180 days[+]	0.062	0.060	0.049	0.054	0.049	0.044
ASTM C 1585, Rate of Water Absorption (Sorptivity), x10^{-4} mm/s$^{1/2}$						
28d accel. cure (Initial/Secondary)	10.0 / 7.5	3.1[*] / 2.8	1.8[*] / 1.7	7.5 / 4.6	4.8[*] / 2.1	2.6[*] / 0.86
56d normal cure (Initial/Secondary)	9.9 / 6.9	6.8 / 2.4[*]	2.6[*] / 1.4	20.0 / 13.0	7.1[*] / 3.3	4.1[*] / 1.9[*]
196d normal cure (Initial/Secondary)	6.8[*] / 6.8	4.1[*] / 1.3	4.9[*] / 1.3	4.1 / 2.4	3.6[*] / 1.8	1.2[*] / 0.82[*]
28d accel. cure (Initial/Secondary), g	1.77 / 6.85	0.82 / 2.59	0.66 / 1.75	1.48 / 4.93	1.20 / 2.71	0.51 / 1.13
56d normal cure (Initial/Secondary), g	1.78 / 6.74	1.06 / 2.94	0.67 / 1.62	2.62 / 12.2	1.4 / 3.76	0.87 / 2.17
196d normal cure (Initial/Secondary), g	1.34 / 5.74	0.96 / 1.81	1.13 / 1.94	1.09 / 2.73	0.95 / 2.12	0.64 / 1.14
ASTM C 1556, Chloride Diffusion, x 10^{-12} m^2/s						
Case 4 [A]	5.28	2.24	0.84	8.64	4.81	0.36
Case 3 [B]	11.8	3.20	1.02	6.45	4.01	0.64

Case 1 [C]	2.28	1.37	0.47	1.74	0.14	0.26
Case 5 [C]	2.36	1.32	0.68	3.91	2.02	0.30
ASTM C 1556, Surface Chloride, % by weight of concrete						
Case 4 [A]	1.12	1.77	1.03	0.96	0.75	3.02
Case 3 [B]	1.02	1.37	1.93	1.23	1.39	2.65
Case 1 [C]	1.01	1.90	2.11	1.26	5.62	1.90
Case 5 [C]	0.78	1.29	1.87	1.19	2.41	2.14

[+] Curing period in 70°F, 50% RH environment NOT included 7 days initial wet curing period in water bath
[*] a correlation coefficient less than 0.98 indicating that the rate cannot be determined according to ASTM C1585

Rapid index tests results were compared with chloride diffusion test data. Research results were presented at the 2009 Concrete Technology Forum in Cincinnatti, OH as "Early Age Tests and Criteria for Predicting Long Term Chloride Penetration into Concrete". Preliminary observations show promising correlations between the early age RCPT results and chloride diffusion coefficients for scenarios Case 1, and Case 3. For Cases 4, and 5 fly ash mixes appear to be more prone to show higher Da's than what the early age RCPT results would have suggested.

Table 2. Yield Adjusted Mixture Proportions and Preliminary Test Results – Chloride Phase II

Calculated Batch Quantities								
	0.39PC	**0.39FA15**	**0.39SL25**	**0.39SF7**	**0.62FA30**	**0.62SL50**	**0.29PC**	**0.39PC**-R**
Type I/II cement, lb/yd^3	612	520	462	565	349	249	803	612
Slag, lb/yd^3	-	-	154	-	-	249	-	-
Fly ash, lb/yd^3	-	92	-	-	149	-	-	-
Silica Fume, lb/yd^3	-	-	-	43	-	-	-	-
SCM, %	0%	15%	25%	7%	30%	50%	0%	0%
Coarse Agg. (No.57), lb/yd^3	2066	2068	2081	2052	2094	2093	2069	2066
Fine Aggregate, lb/yd^3	1331	1296	1331	1307	1216	1258	1183	1331
Mixing Water, lb/yd^3	238	239	240	237	287	290	236	238
w/cm	0.39	0.39	0.39	0.39	0.58	0.58	0.29	0.39
ASTM C494 Type A, oz/cwt	4	4	4	4	3	3	5	4
ASTM C494 Type F, oz/cwt	8.8	8.3	6.9	8.2	-	-	11.7	8.4
Fresh Concrete Properties								
ASTM C143, Slump, in.	5	6 1/2	7 3/4	6	6 1/2	7	8 3/4	7
ASTM C231, Air, %	1.8	1.6	1.2	1.8	1.6	1.4	1.1	1.7
ASTM C138, Density, lb/ft^3	158.1	156.9	158.9	156.5	152.5	154.1	159.7	158.1
ASTM C1064, Temperature, °F	75	75	75	75	75	75	76	76
Hardened Concrete Properties								
ASTM C39, Compressive Strength, psi								
28 days	10,460	9,590	10,300	10,740	3,880	5,380	13,480	9,890

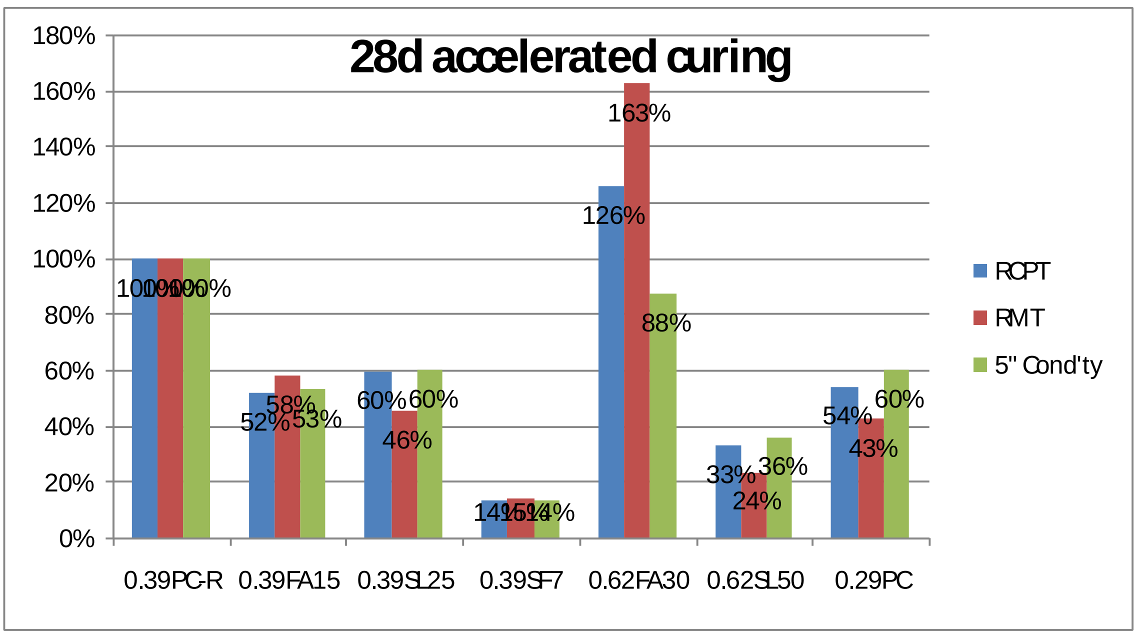
Draft ASTM Standard, Water Absorption Test at 60 °C, %								
56d normal cure	1.03	1.02	1.00	0.82	1.88	1.75	0.91	-
ASTM C1202, Rapid Chloride Permeability, Coulombs								
28d accelerated cure	2180$^-$	1031	1186	276	2495	661	1078	1980
56d normal cure	1722	1557	1272	299	4012	832	1209	-
196d normal cure	on-going	on-going	on-going	on-going	on-going	on-going	on-going	-
Draft ASTM Standard, 5 minute Conductivity, Sm^{-1}								
28d accelerated cure	0.010$^-$	0.005	0.006	0.001	0.009	0.004	0.006	0.010
56 normal cure	0.009	0.007	0.006	0.001	0.012	0.003	0.006	-
196d normal cure	on-going	on-going	on-going	on-going	on-going	on-going	on-going	-
AASHTO TP64, Rate of Penetration (RMT), mm/(V-hr)								
28d accelerated cure	0.034$^-$	0.017	0.013	0.004	0.047	0.007	0.012	0.029
56d normal cure	0.027	0.017	0.011	0.004	0.046	0.012	0.011	-
196d normal cure	on-going	on-going	on-going	on-going	on-going	on-going	on-going	-
ASTM C157, Length Change (Drying Shrinkage), %								
28 days$^+$	0.032 %	0.037%	0.032%	0.028%	0.041%	0.044%	0.024 %	-
56 days$^+$	0.039 %	0.047%	0.038%	0.034%	0.054%	0.052%	0.029 %	-
90 days$^+$	0.042 %	0.054%	0.047%	0.043%	0.064%	0.053%	0.030 %	-
180 days$^+$	0.049 %	0.056%	on-going	on-going	on-going	on-going	on-going	-
ASTM C 1585, Rate of Water Absorption (Sorptivity), x10^{-4} mm/$s^{1/2}$								
28d accel. cure (Initial/Secondary)	-	3.1 / 2.1	4.7 / 2.0*	3.3 / 2.1	9.6 / 3.8	7.6 / 2.8	3.1 / 2.6	9.5 / 5.2
56d normal cure (Initial/Secondary)	5.9 / 3.3*	6.1 / 4.1	3.1* / 1.5*	3.1 / 1.9*	9.9 / 7.0	7.1* /2.8*	2.1*/ 2.9	-
196d normal cure (Initial/Secondary)	on-going	on-going	on-going	on-going	on-going	on-going	on-going	-
28d accel. cure (Initial/Secondary), g	-	0.5 /1.9	0.9 / 2.2	0.6 / 1.9	1.8 / 4.4	1.9 / 3.7	0.5 / 2.2	1.6 / 5.1
56d normal cure (Initial/Secondary), g	1.1 / 3.2	0.9 /3.8	0.8 / 1.7	0.6 / 1.7	2.3 / 6.9	2.1 / 3.9	0.5 / 2.4	-
196d normal cure (Initial/Secondary), g	on-going	on-going	on-going	on-going	on-going	on-going	on-going	-
ASTM C 1556, Chloride Diffusion, x 10^{-12} m^2/s								
56d nc + 35d in solution	on-going	on-going	on-going	on-going	on-going	on-going	on-going	-
6m nc + 35d in solution	on-going	on-going	on-going	on-going	on-going	on-going	on-going	-
6m nc + 12m in solution	on-going	on-going	on-going	on-going	on-going	on-going	on-going	-
56d nc + 21w cyclic exposure (3d solution+ 4d air)	on-going	on-going	on-going	on-going	on-going	on-going	on-going	-
56d nc + 75w cyclic exposure (3d solution+ 4d air)	on-going	on-going	on-going	on-going	on-going	on-going	on-going	-
ASTM C 1556, Surface Chloride, % by weight of concrete								
56d nc + 35d in solution	on-going	on-going	on-going	on-going	on-going	on-going	on-going	-
6m nc + 35d in solution	on-going	on-going	on-going	on-going	on-going	on-going	on-going	-
6m nc + 12m in solution	on-going	on-going	on-going	on-going	on-going	on-going	on-going	-

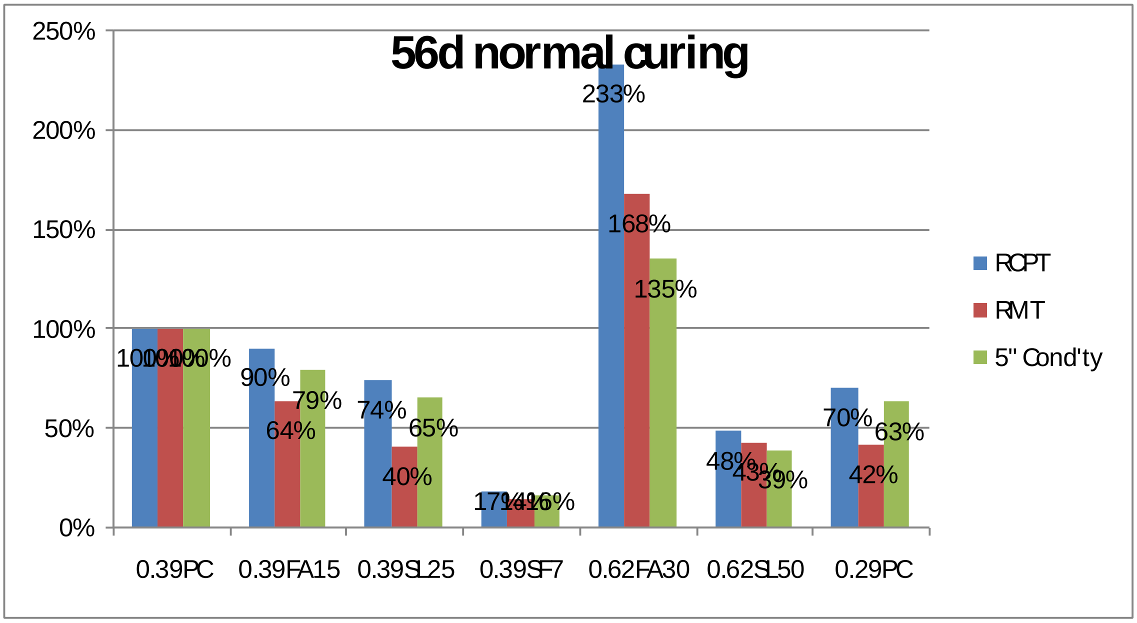
56d nc + 21w cyclic exposure (3d solution+ 4d air)	on-going	on-going	on-going	on-going	on-going	on-going	on-going	-
56d nc + 75w cyclic exposure (3d solution+ 4d air)	on-going	on-going	on-going	on-going	on-going	on-going	on-going	-

[-] Tested at 21d instead of 28d
[+] Curing period in 70°F, 50% RH environment NOT included 7 days initial wet curing period in water bath
[*] A correlation coefficient less than 0.98 indicating that the rate cannot be determined according to ASTM C1585
[**] Exact repeat of designated mixture

Preliminary Observations

1. The 28 day accelerated cured and 56 day moist cured RCPT, RMT, and conductivity test results appear to be proportional to each other except for Mix 0.62FA30. This becomes clear from the plot below. Mix 0.62FA30 has high permeability at 56 days (4000+ coulombs) and it is well known that at such levels the RCPT tends to increase coulombs due to over-heating. RMT for those types of mixtures is also questionable because the initial current was at the border line for voltage choice and the chloride had passed throughout the depth. For these high permeability mixes the 5 minute Conductivity results are most dependable as the specimens do not heat up.





2. Based on the early age 5 minute Conductivity test results the mixtures in the order of chloride penetration (lowest to highest) are as follows: 0.39SF7<0.62SL50<0.39FA15=0.39SL25=0.29PC<0.39PC<0.62FA30
This exactly matches the permeability classifications shown in the Table in the last page. The primary difference is the very low chloride penetration values of the 0.62SL50. It would be interesting to observe if the chloride diffusion coefficient test results would follow the same trend and particularly for the 062 SL50 mixture. The chloride diffusion tests for the first condition has been completed now. Data analysis is ongoing. It is important to observe if the rapid index vs Cl diff coeff. test result correlations are independent of SCM types, dosage, and w/cm.
3. Water absorption and sorptivity test results did not classify the mixtures so effectively as RCPT, RMT, and 5 min. conductivity. However higher w/cm mixtures gave higher absorption values. If the higher w/cm mixtures showed higher chloride diffusion coefficients it is possible to use the absorption tests to eliminate those mixtures.

Field Core Testing Program (PROPOSED NO COST ADDITIONAL WORK BY NRMCA)

In addition to that lab experimental program it would be useful to get concrete cores from un-cracked areas from 10-30 years old structures in bridge deck (low relative humidity), bridge deck (high relative humidity), marine - submerged, tidal, spray zones. These samples would be used by NRMCA to measure sorptivity, chloride profile on top 2 in., discard the next 1 inch and conduct ASTM C1556 chloride diffusion test on next 2 inches. Do 2 rapid index test results (RCPT, gas permeability) from sample just below that. So a 7 to 10 in. core thickness of 4 in. diameter may be required for this program. The aim would be to see if there is a unique relation between measured rapid index test result and calculated chloride diffusion coefficient from chloride profile. Also it would be worthwhile to compare those diffusion coefficients with mixture proportions and the 56 day rapid index results attained during quality assurance or mix qualification stage (if such is available). The core test program can account for a wide range of field conditions such as moist curing durations, wet/dry chloride exposures, chloride loadings and temperature exposures.

Freeze Thaw - Test Methods, Curing Conditions and Test Ages

Freeze thaw (F-T) attack is another major concrete deterioration mechanism. Capillary sorption and water vapor diffusion are the two principal transport mechanisms that cause critical saturation of capillary pores which is necessary for freeze thaw damage. An air content of 5% to 7% with an air voids spacing factor less than 0.2 µm is typically necessary to maintain adequate freeze thaw resistance. While the air entrainment requirement is acceptable an attempt will be made to develop test and performance criteria as an alternative to the maximum w/cm requirement. ACI 318 states that for F1, F2, F3 categories max w/cm=0.45, min strength=4500 psi, and air content limits. It is clear that a low w/cm is required to ensure low water penetration and potential for critical saturation. By conducting mixes with different w/cm and various SCM dose and contents we will examine if F-T performance (as measured by no. of cycles for 15% mass loss or relative dynamic modulus of elasticity after 300 cycles) is better correlated with a rapid index test such as sorption or gas permeability criteria than w/cm. If at each w/cm, F-T performance varies widely depending on the test criteria the importance of the test criteria as opposed to w/cm is established. Also it would be determined whether some mixes with low w/cm and higher sorptivity/gas perm can have poorer F-T performance as compared to mixes with higher w/cm and lower sorptivity/gas perm which can again establish the importance of the test criteria as opposed to w/cm.

ACI 318-08 F classes

Moderate F1: Concrete exposed to freezing-and thawing cycles and occasional exposure to moisture
Severe F2: Concrete exposed to freezing-and thawing cycles and in continuous contact with moisture
Very severe F3: Concrete exposed to freezing-and thawing and in continuous contact with moisture and exposed to deicing chemicals

From the test results plots Concrete class F2 can be suggested to have RDM of 60-80% while F3 can have RDM>80% after 300 F-T cycles. It is hoped that these RDM and mass loss correlates with rapid index test criteria such as sorptivity and we can use those test criteria rather than RDM.

For C672 Y axis will be mass loss or visual rating

Mixture Proportions Planned

w/cm	PC	20%FA	30%SL	25%SL+5%SF
0.40	Yes-m			Yes-vl
0.45	Yes-m	Yes-m	Yes-m	Yes-vl
0.50	Yes-h	Yes-m	Yes-m	Yes-l
0.60	Yes-h			Yes-m

May add some more mixes with different cement and aggregates

Crushed coarse aggregate (1.0" max) no. 57, natural sand FM=2.88
Adjust water reducer or high range water reducer (if any) for desired slump = 5 to 7 in.
Air entrained concrete mixtures – Target 5 to 6% air. Use AEA from same admix manufacturer

Normal Curing – Standard moist room curing starts immediately after making the specimens
Accelerated Curing – 7 days of normal curing followed by 21 days of curing in 100F water

For all mixtures measure the following: Slump, temperature, air content, density, Strength (28 days of moist curing followed by 28 days of air drying), Shrinkage (7 days moist curing followed by 90 days of air drying).

Durability Tests

For all tests at all ages, make 2 cylinders unless otherwise stated. Make 6 extra cylinders for each mix, moist cure for 28 days and then ship 4 to Purdue/UT for gas permeability testing and keep the other 2.

Rapid Chloride Permeability test (ASTM C1202)
i) 28 day accelerated
ii) 56 day normal curing
iii) 26 week (182 d) normal curing

ASTM C666. Test 2 replicate specimens as recommended by C666 standard. 28 day moist curing followed by 28 day air drying in 50% RH and 70F and then start C666. Do dynamic modulus, mass change tests as required by C666. Do test until 1000 cycles or visible differences between mixtures which-ever occurs first. Also mixtures should not be tested for >25% mass reduction or 50% relative dynamic modulus of elasticity.

ASTM C672. Test 2 replicate specimens as recommended by C672 standard. 28 day moist curing followed by 28 day air drying in 50% RH and 70F and then start C672. Do test until 150 cycles or visible differences between mixtures which-ever occurs first. Measure mass loss and visual rating every 5 cycles.

Sorptivity Test (ASTM C1585) after:
i) 28 day accelerated + 18 d specimen conditioning (C1585)
ii) 38 day normal curing + 18 d specimen conditioning (C1585)
iii) 26 week (182 d) normal curing + 18 d specimen conditioning (C1585)

Absorption test BS 1881:122 – use latest ASTM draft
i) 28 day accelerated + 3 d in oven
ii) 56 day normal curing + 3 d in oven
iii) 26 week (182 d) normal curing + 3 d in oven

Table 3. Yield Adjusted Mixture Proportions and Preliminary Test Results

Calculated Batch Quantities											
	0.57 PC	**0.50 PC**	**0.50 FA20**	**0.50 SL30**	**0.50 SL25SF 5**	**0.60 SL25SF 5**	**0.45 PC**	**0.45 SL30**	**0.57 PC**-R**	**0.50 PC**-R**	**0.50 SL30**-R**
Type I/II cement, lb/yd^3	506	539	442	385	385	353	592	414	505	541	382
Slag, lb/yd^3				165	137	126		177			164
Fly ash, lb/yd^3			111								
Silica Fume, lb/yd^3					27	25					
SCM, %	0	0	20	30	30	30	0	30	0	0	30
Coarse Agg. (No.57), lb/yd^3	2087	2021	2071	2060	2058	2077	2035	2029	2082	2026	2043
Fine Aggregate, lb/yd^3	1094	1083	1066	1093	1084	1072	1062	1048	1118	1086	1084
Mixing Water, lb/yd^3	290	270	276	275	275	302	267	266	293	270	273
w/cm	0.57	0.50	0.50	0.50	0.50	0.60	0.45	0.45	0.58	0.50	0.50
ASTM C494 AEA, oz/cwt	3.8	4.4	23.5	6.3	4.4	7.0	4.4	6.9	3.8	4.4	4.8
ASTM C494 Type F, oz/cwt		3.1	2.2	3.2	5.5	2.6	8.1	11		6.7	12.8
Fresh Concrete Properties											
ASTM C143, Slump, in.	7	6	6	5	5	6.5	5.25	6	5.5	4.75	7
ASTM C231, Air, %	6	7.2	6	6.2	6.5	6.2	7	7.6	5.8	7.2	7.2
ASTM C138, Density, lb/ft^3	148.1	145.7	147.7	148.1	147.7	147.3	147.3	146.5	148.9	146.1	146.9
ASTM C1064, Temperature, °F	75	75	73	70	72	70	70	70	70	70	68
Hardened Concrete Properties											
ASTM C39, Compressive Strength, psi											
28 days	4,918	4,895	4,101	5,376	6,249	4,844	5,427	5,182	4,738	4,454	5,312
Draft ASTM Standard, Water Absorption Test at 50 °C, %											
28d accelerated cure	-	-	1.41	-	1.24	1.56	1.61	1.2	2.28	1.81	1.47
56d normal cure	1.85	1.65	1.81	1.36	1.44	1.74	1.76	1.39	-	-	-
182d (26w) normal cure	On-going	On-going	On-going	On-going	On-going	On-going	On-going	On-going	-	-	-
ASTM C1202, Rapid Chloride Permeability, Coulombs											
28d accelerated cure	-	-	2014	-	332	516	2630	851^{-}	5015	3578	1077
56d normal cure	4876	3633	4287	1554	469	848	2957	1143^{-}	-	-	-
182d (22w) normal cure	On-going	On-going	On-going	On-going	On-going	On-going	On-going	On-going	-	-	-
ASTM C157, Length Change (Drying Shrinkage), %											
28 days^{+}	0.045%	0.039%	0.041%	0.049%	0.053%	0.063%	0.036%	0.039%	-	-	-
56 days^{+}	0.061%	0.046%	0.050%	0.052%	0.056%	0.069%	0.049%	0.049%	-	-	-
90 days^{+}	On-going	On-going	On-going	On-going	On-going	On-going	On-going	On-going	-	-	-
180 days^{+}	On-going	On-going	On-going	On-going	On-going	On-going	On-going	On-going	-	-	-
ASTM C 1585, Rate of Water Absorption (Sorptivity), x10^{-4} mm/s$^{1/2}$											
28d accelerated cure (Initial/Secondary)	On-going	On-going	On-going	On-going	On-going	On-going	On-going	On-going	-	-	-
56d normal cure (Initial/Secondary)	On-going	On-going	On-going	On-going	On-going	On-going	On-going	On-going	-	-	-
196d normal cure (Initial/Secondary)	On-going	On-going	On-going	On-going	On-going	On-going	On-going	On-going	-	-	-
28d accel. cure (Initial/Secondary), g	On-going	On-going	On-going	On-going	On-going	On-going	On-going	On-going	-	-	-
56d normal cure (Initial/Secondary), g	On-going	On-going	On-going	On-going	On-going	On-going	On-going	On-going	-	-	-
196d normal cure (Initial/Secondary), g	On-going	On-going	On-going	On-going	On-going	On-going	On-going	On-going	-	-	-
ASTM C 666, Freezing and Thawing Resistance											
Durability Factor	On-going	On-going	On-going	On-going	On-going	On-going	On-going	On-going	-	-	-

Mass loss	On-going	On-going	On-going	On-going	On-going	On-going	On-going	On-going	-	-	-
ASTM C 672, Salt Scaling Resistance											
Visual Rating (0 – 5)	On-going	On-going	On-going	On-going	On-going	On-going	On-going	On-going	-	-	-

** Exact repeat of designated mixture
+ Curing period in 70°F, 50% RH environment NOT included 7 days initial wet curing period in water bath
- Result of only one specimen

The freeze thaw tests and scaling are ongoing. Even after 200 F-T cycles most of the mixtures appear in an excellent condition. Scaling tests are ongoing as well. Some of these results would become available in the next quarter.

Over the Next Quarter

The following work will be completed in quarter Jan-March 2010.

1. 6 month rapid index test results and chloride diffusion test data from 3 different conditions (Table 2) would become available and comparisons with rapid index test results can be made.
2. Most of the rapid index test results and some of the freeze thaw and scaling test results (Table 3) will become available and preliminary comparisons can be made.
3. A complete experimental plan for sulfate testing will be detailed and some of the mixtures will be cast.